# Heavy Flavor Measurements in Heavy Ion Collisions by PHENIX at RHIC

## (Recent J/ψ Results from PHENIX)

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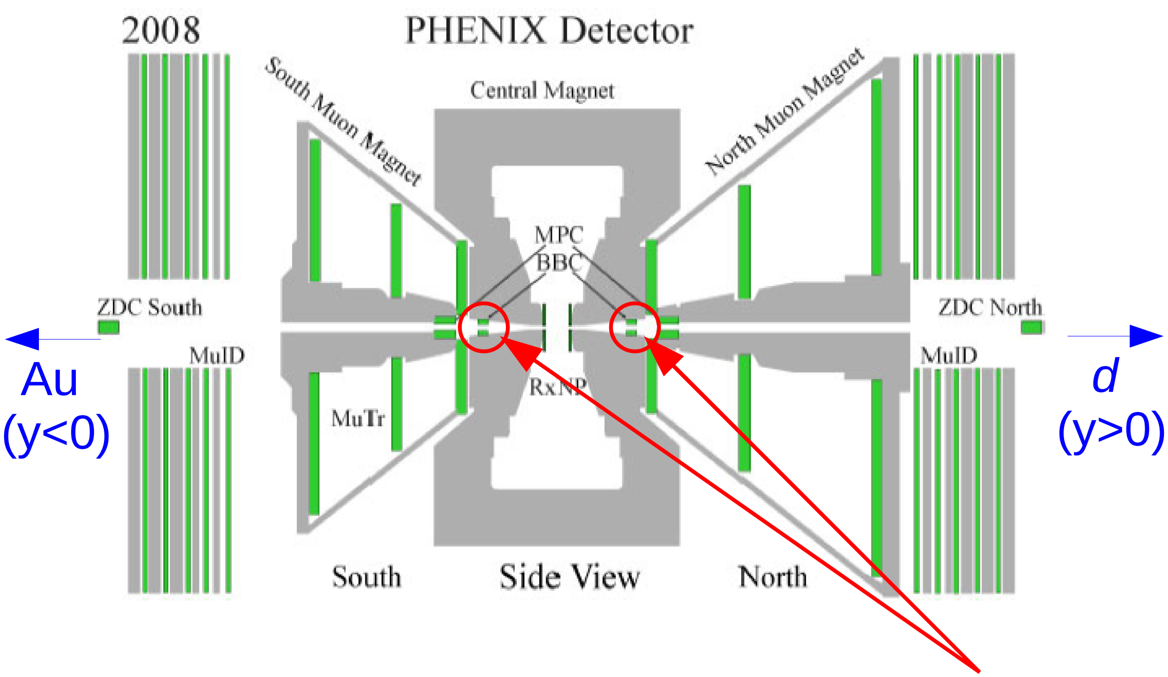
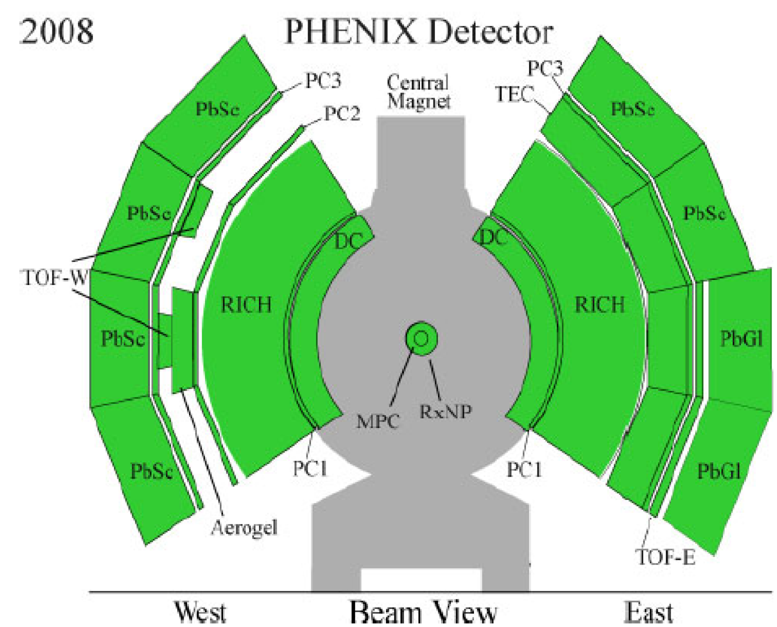
PANIC 2011

# The PHENIX Detector

## 2008 Run




### Muon Arms

- Muons
- $1.2<|\eta|<2.4$
- $\Delta\varphi = 2\pi$
- $J/\psi \rightarrow \mu^+\mu^-$

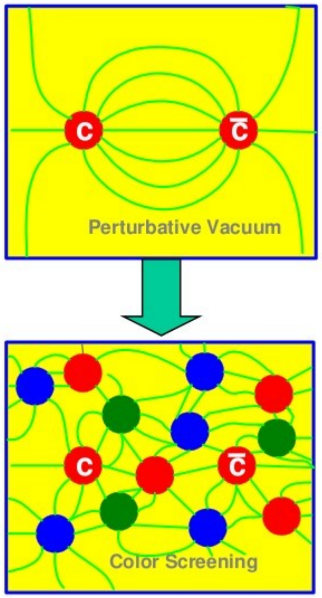
### Beam-Beam Counters

- Measure Centrality (impact parameter) as a percentage of BBC charge

### Central Arms

- Charged particles
- $\eta<|0.35|$
- $\Delta\varphi = \pi$
- $J/\psi \rightarrow e^+e^-$

# Closed Heavy Flavor: Quarkonia



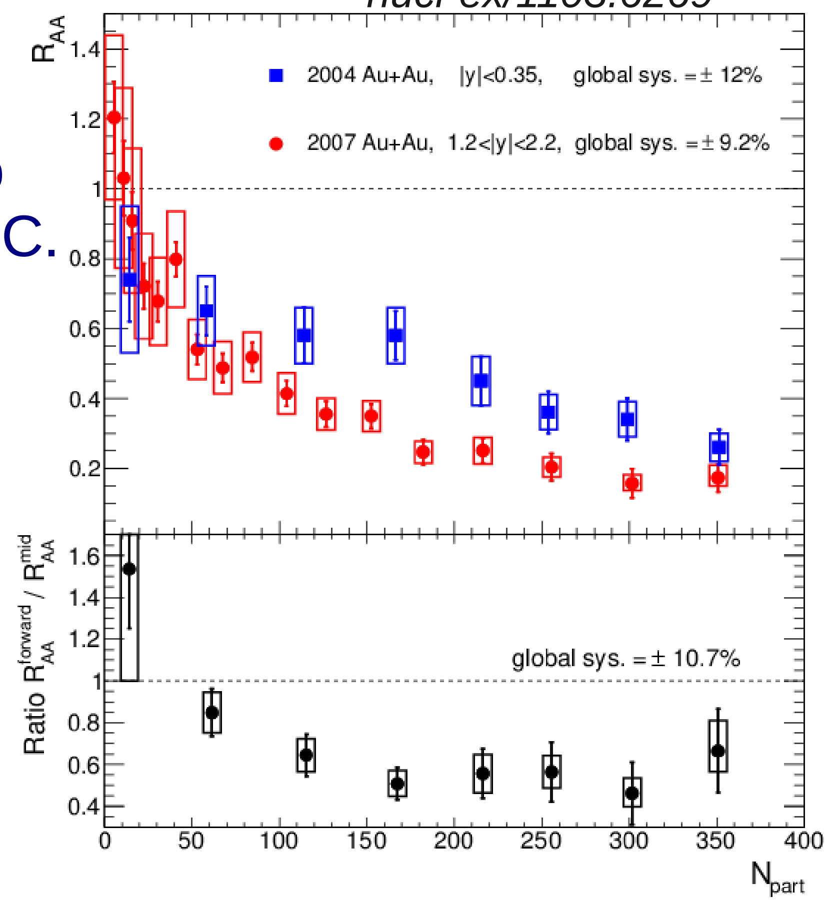

## Goal: Measure the screening length in the QGP

Quarkonia is our best tool for measuring this directly!

$$R_{AA} = \frac{dN^{AA}/dy}{dN^{pp}/dy\, N_{Coll}}$$

*nucl-ex/1103.6269*

Significant suppression of J/ψ production in Au+Au relative to p+p collisions observed at RHIC.




Different Suppression at different rapidity! Why?

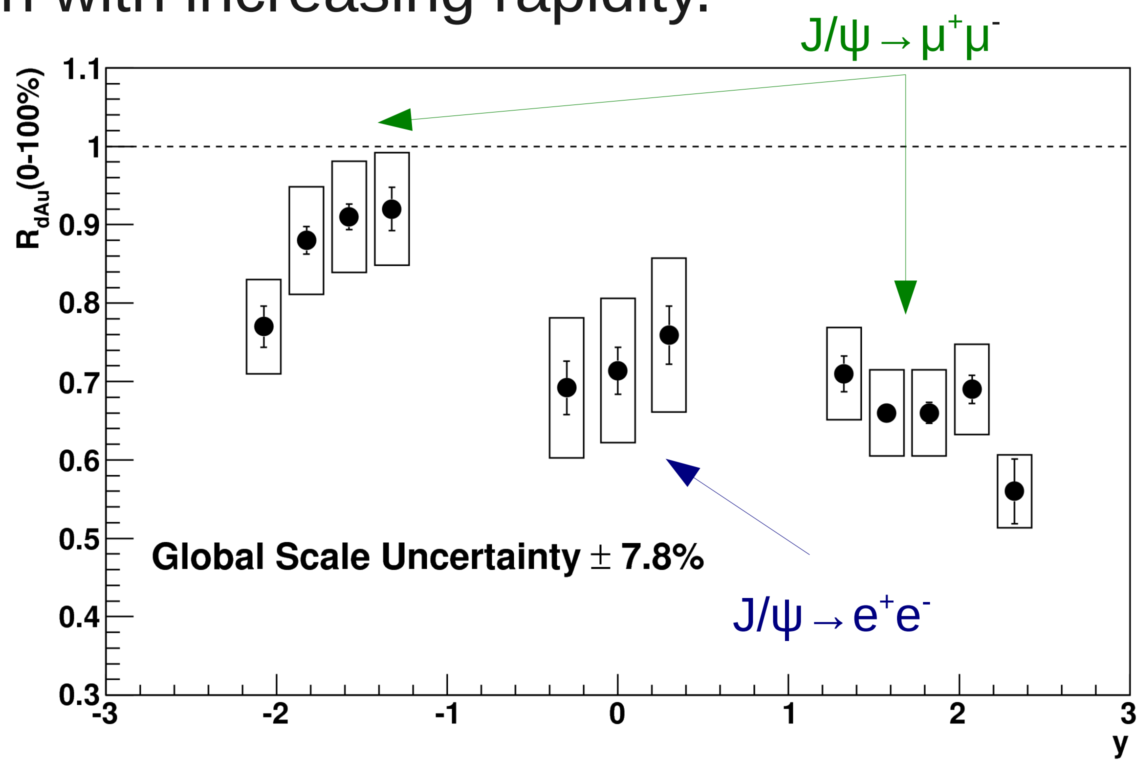
What about the effect of producing a J/ψ in a nuclear target (cold nuclear matter effects)?

Need to understand our baseline in order to extract hot nuclear matter effects!

# Understanding our Baseline

- New large statistics d+Au data taken @ 200 GeV in 2008.
- This allows us to study Cold Nuclear Matter (CNM) effects directly.
- Minimum Bias (centrality integrated) $R_{dAu}$ results shown here.
- Shows increasing suppression with increasing rapidity.

$$R_{dAu}(i) = \frac{dN^{dAu}_{J/\psi}/dy(i)}{\langle N_{coll}(i)\rangle dN^{pp}_{J/\psi}/dy}$$




*arXiv:nucl-ex/1010.1246*

**Vertical Error bars** – point-to-point uncorrelated errors
**Boxes** - point-to-point correlated errors

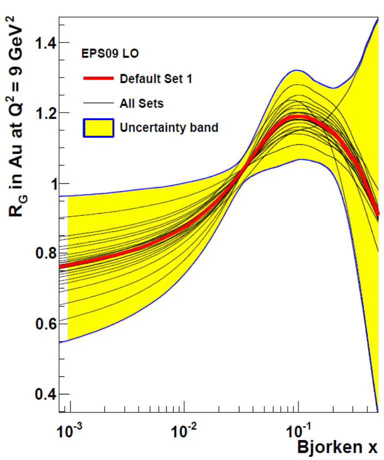
# Theoretical Calculations

1) 1st Calculation includes two components.

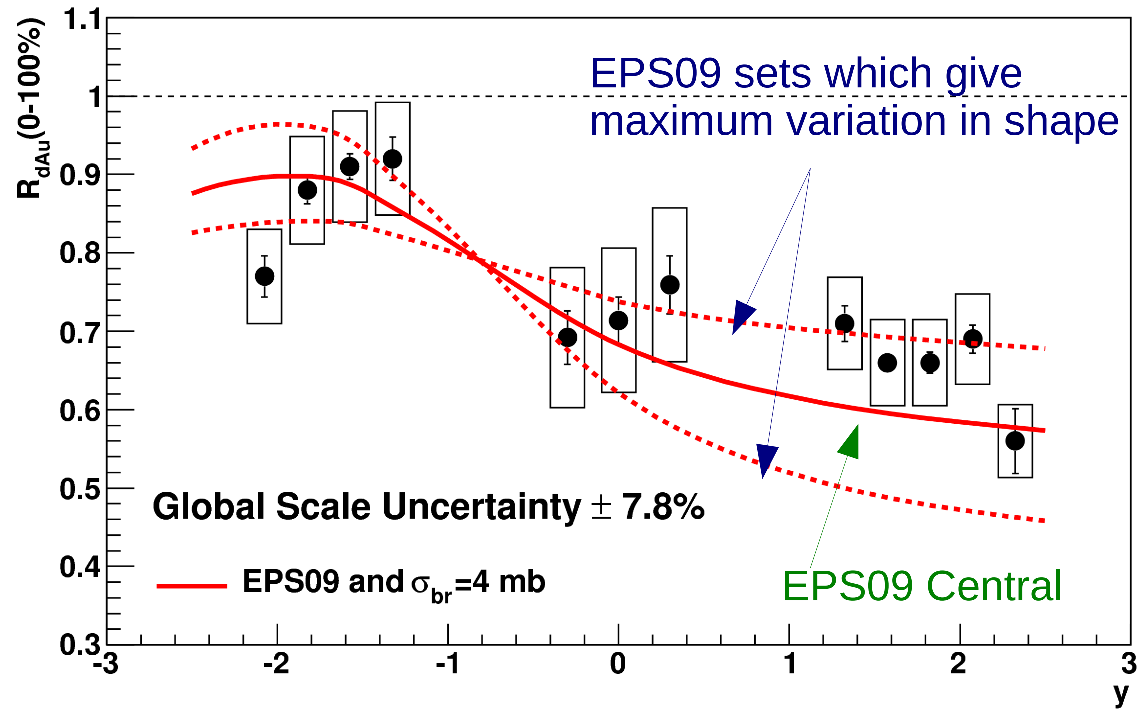
   1) Gluon modification (shadowing) from EPS09 nPDF – parametrization of DIS+pA data.
      - Calculations are modification vs. nucleon impact parameter ($r_T$) in the Au nucleus.
      - Fold $r_T$ distribution with PHENIX centrality distributions calculated from Glauber MC.

   2) Nuclear Break-up cross section $\sigma_{br}$ – due to collisions of J/ψ with nucleons
      - $\sigma_{br}$=4 mb chosen to match backward rapidity data.

- Shows reasonable agreement over all rapidity, as expected for MB data.




LO EPS09 $R_G$ vs. Bjorken x for Au ← no intrinsic centrality dependence

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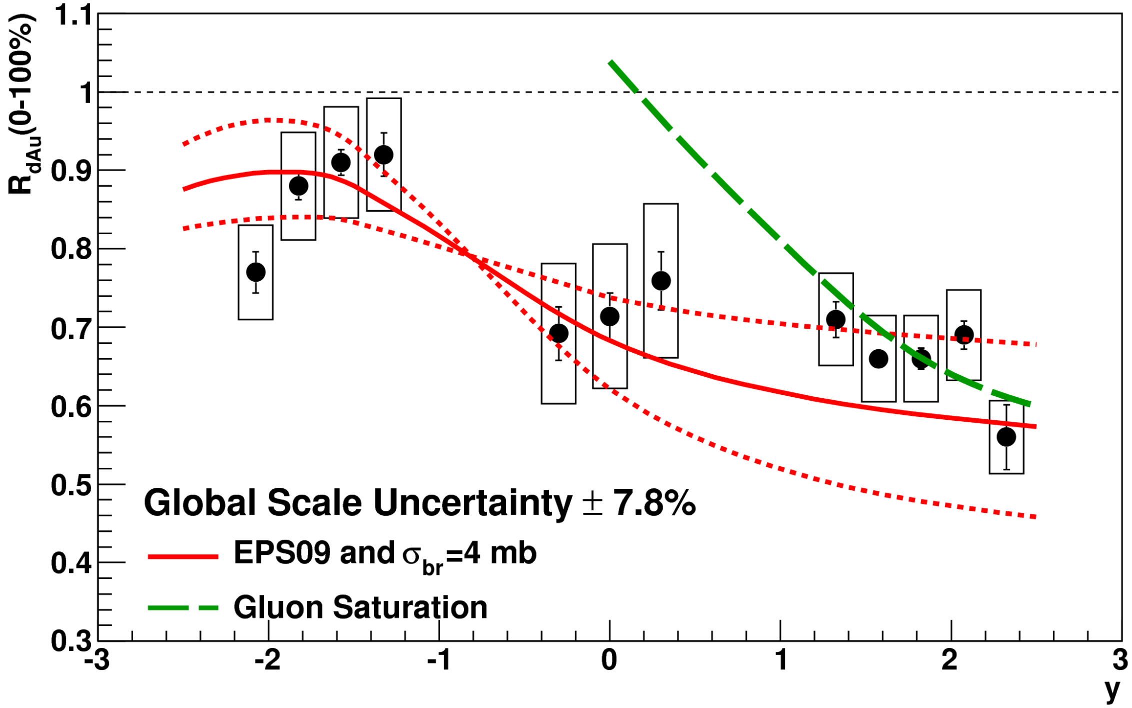
2) Calculation by Kharzeev and Tuchin *(Nucl. Phys. A 770 (2006)40)*
   - Includes Gluon Saturation at low x
   - Shows good agreement @ +y.
   - Unrealistic at backward and mid rapidity.
   - Validity uncertain for peripheral events?

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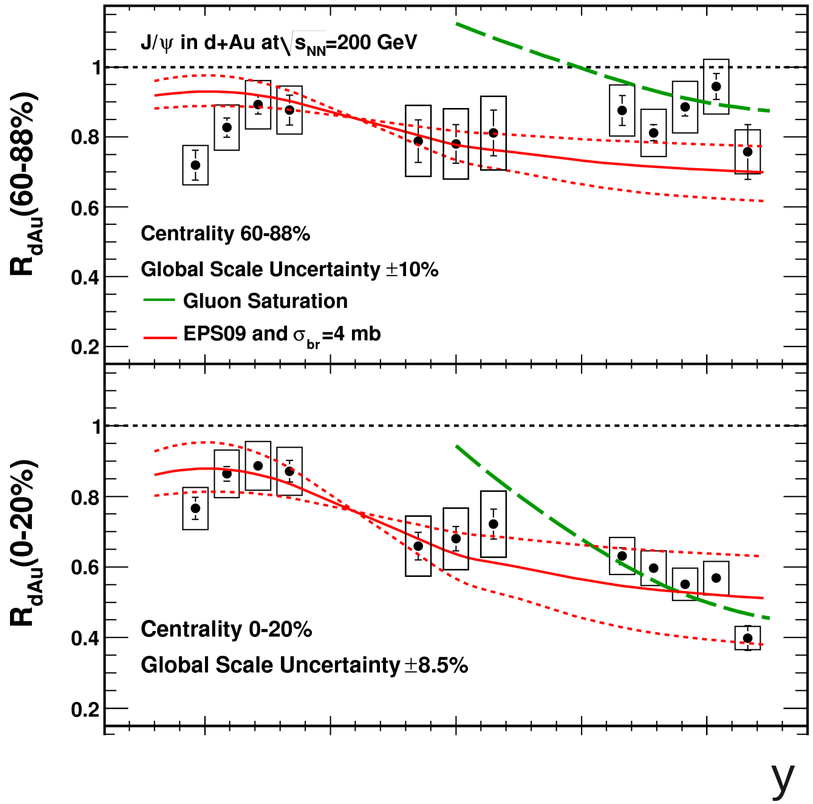
# Centrality Dependent $R_{dAu}$

- Want to investigate centrality (impact parameter) dependence.
  - Divide into percentage bins based on BBC charge (0% - most central, 100% - most peripheral.
- Calculations by the same models as detailed on previous slide.
  - Must introduce centrality dependence into EPS09 – **arbitrarily** choose linear dependence on nuclear thickness (common assumption).
  - Shadowing + break-up does not describe forward rapidity data for peripheral collisions.
  - Gluon saturation model still describes data well at +y.

*arXiv:nucl-ex/1010.1246*



# Centrality Dependent $R_{dAu}$

- Take the ratio of central $R_{dAu}$ to peripheral $R_{dAu} \rightarrow R_{cp}$
  - Significant reduction of systematic errors
  - Shadowing + $\sigma_{br}$ describes backward & midrapidity well.
  - Failure of Shadowing + $\sigma_{br}$ to describe $R_{cp}$ at large y seems to be due to poor description of centrality dependence.
  - Gluon saturation model appears to provide a better description of the centrality dependence, although it is not clear how reliable it is for peripheral collisions where there should be less coherent effects.

$$R_{cp}(0-20\%) = \frac{R_{dAu}(0-20\%)}{R_{dAu}(60-88\%)}$$

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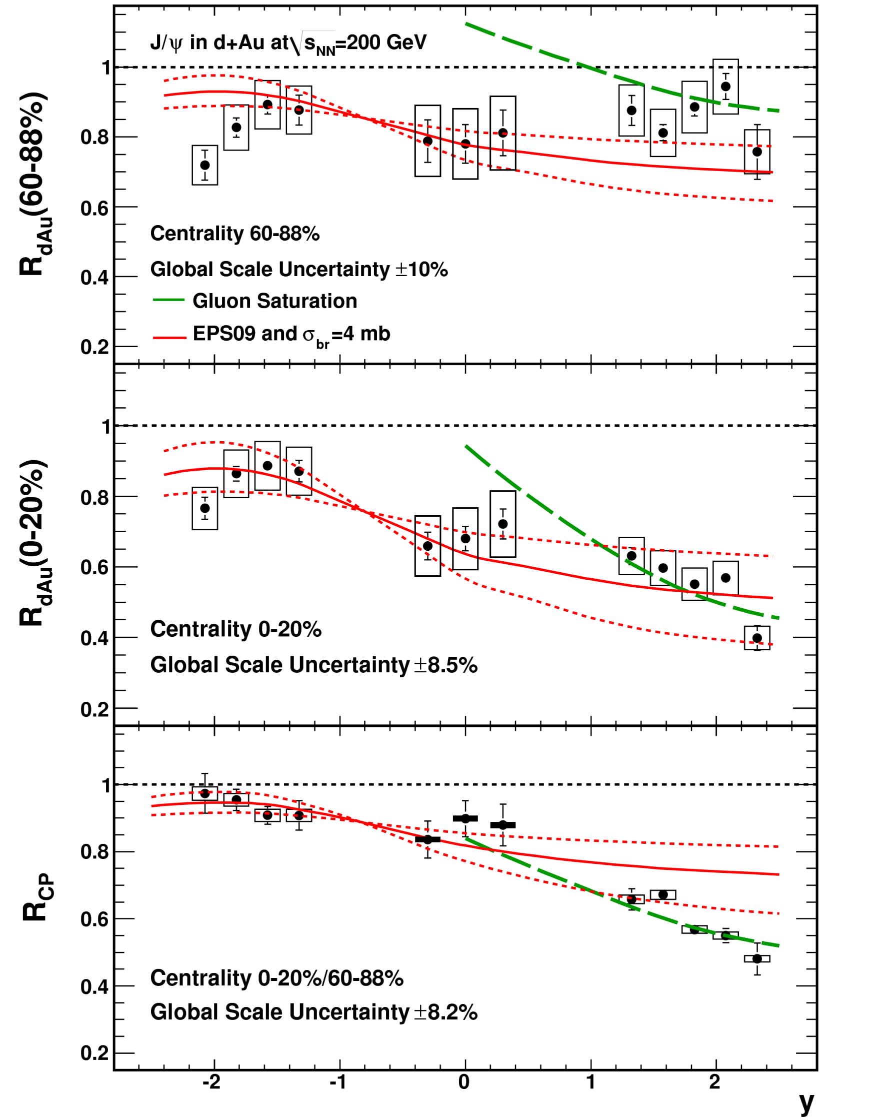
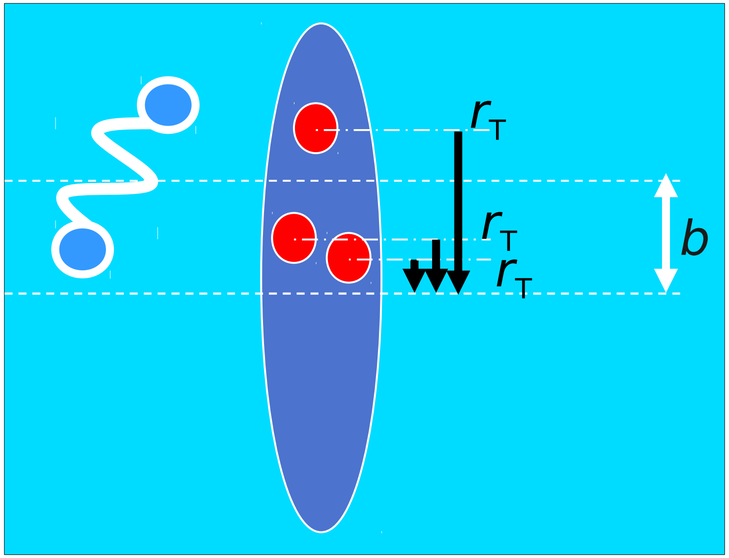
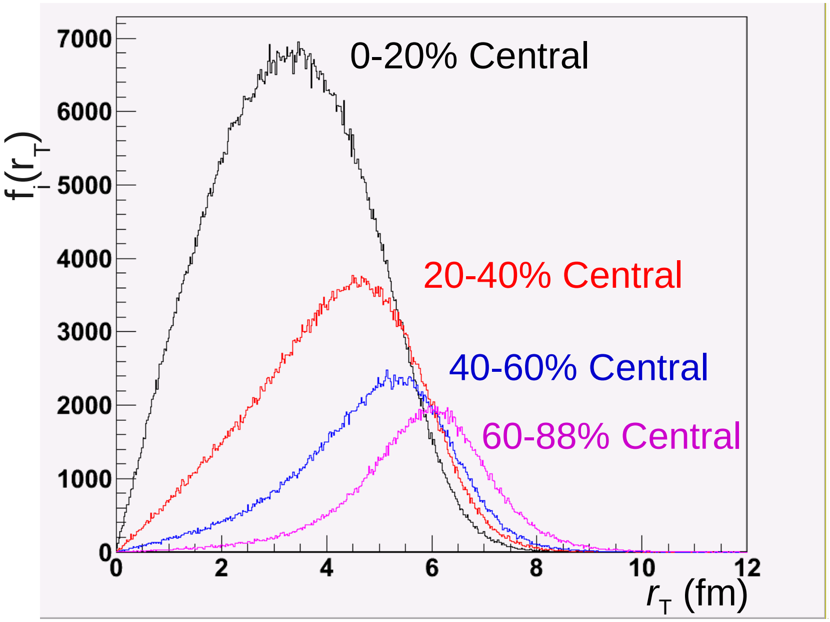


# Simple Geometrical Model

- Would like to understand how the suppression depends on centrality.
- In d+Au relevant parameter is transverse position of the struck nucleon in each N-N collision → $r_T$
- Use Glauber MC of N-N hit positions in d+Au events to generate $r_T$ distributions.




- Use a simple parametrization of the nuclear modification based on the density weighted longitudinal thickness in the Au nucleus → $\Lambda(r_T)$ [nucleons/fm$^2$].

$$\Lambda(r_T) = \frac{1}{\rho_0} \int dz \, \rho(z, r_T)$$

Woods-Saxon

Resulting $r_T$ distributions from MC for PHENIX centrality bins.

# $R_{dAu}$ from Geometric Modification

Consider, for example, three functional forms for the nuclear modification vs nuclear thickness at $r_T$, $\Lambda(r_T)$, with one free strength parameter *a*

$$M(r_T, a) = 1 - a\Lambda(r_T)$$

$$M(r_T, a) = 1 - a\Lambda(r_T)^2$$

$$M(r_T, a) = e^{-a\Lambda(r_T)}$$

The modification factor $R_{dAu}$ for a given centrality bin (*i*) is then given by

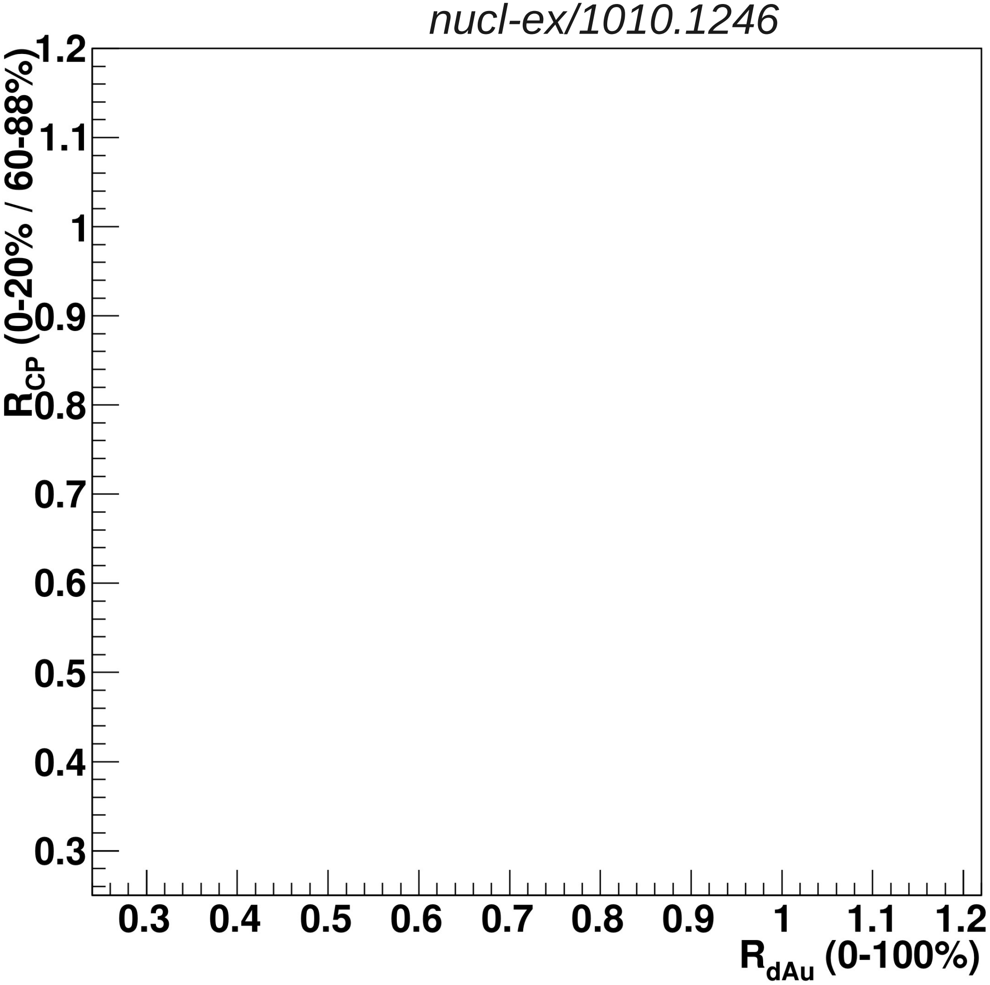
$$R_{dAu,i}(a) = \int f_i(r_T) M(r_T, a)\, dr_T$$

$r_T$ distributions from PHENIX MC

Modification vs $\Lambda(r_T)$ and free parameter *a*

# A Different Way to Look at the Centrality Dependence

- $R_{dAu}$(0-100%) is a measure of the **average** suppression.
- $R_{cp}$ is a measure of the **change** in suppression from central to peripheral events.



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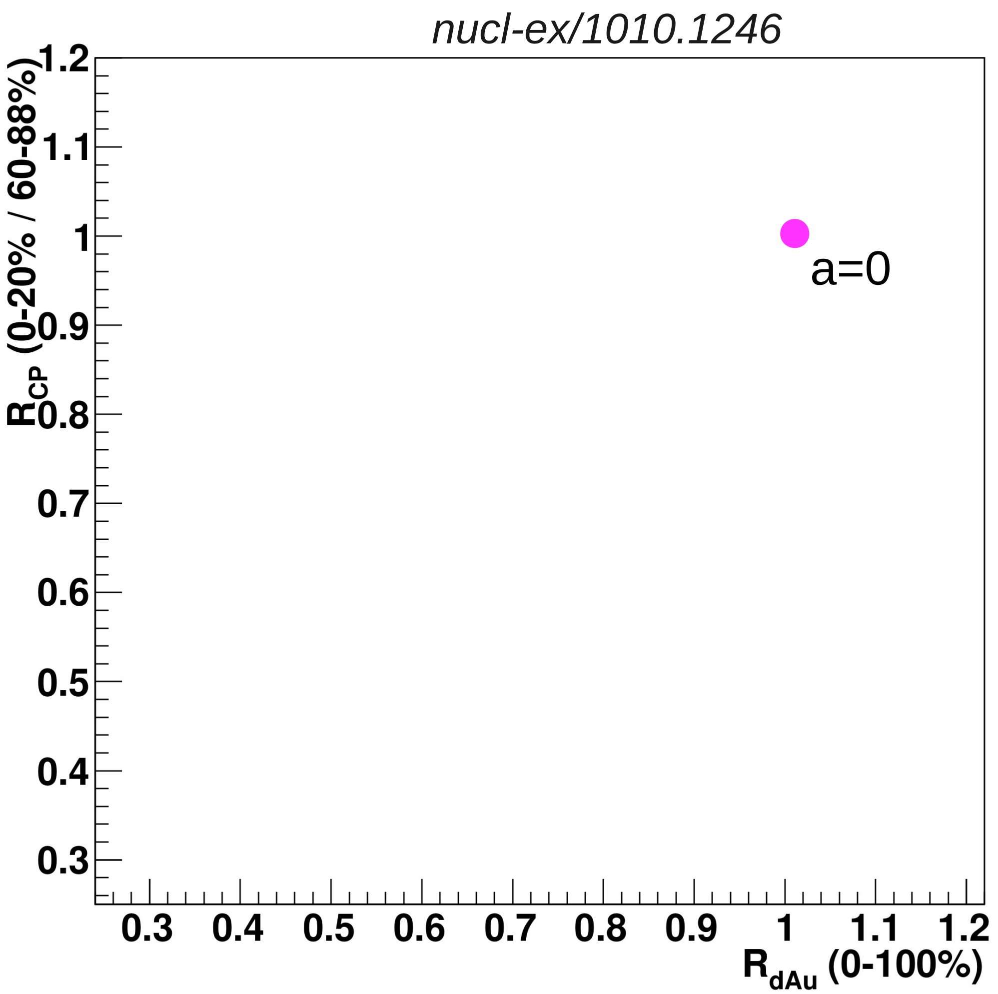
- Any value of parameter *a* translates to a unique point on the $R_{cp}$ – $R_{dAu}$(0-100%) plane.



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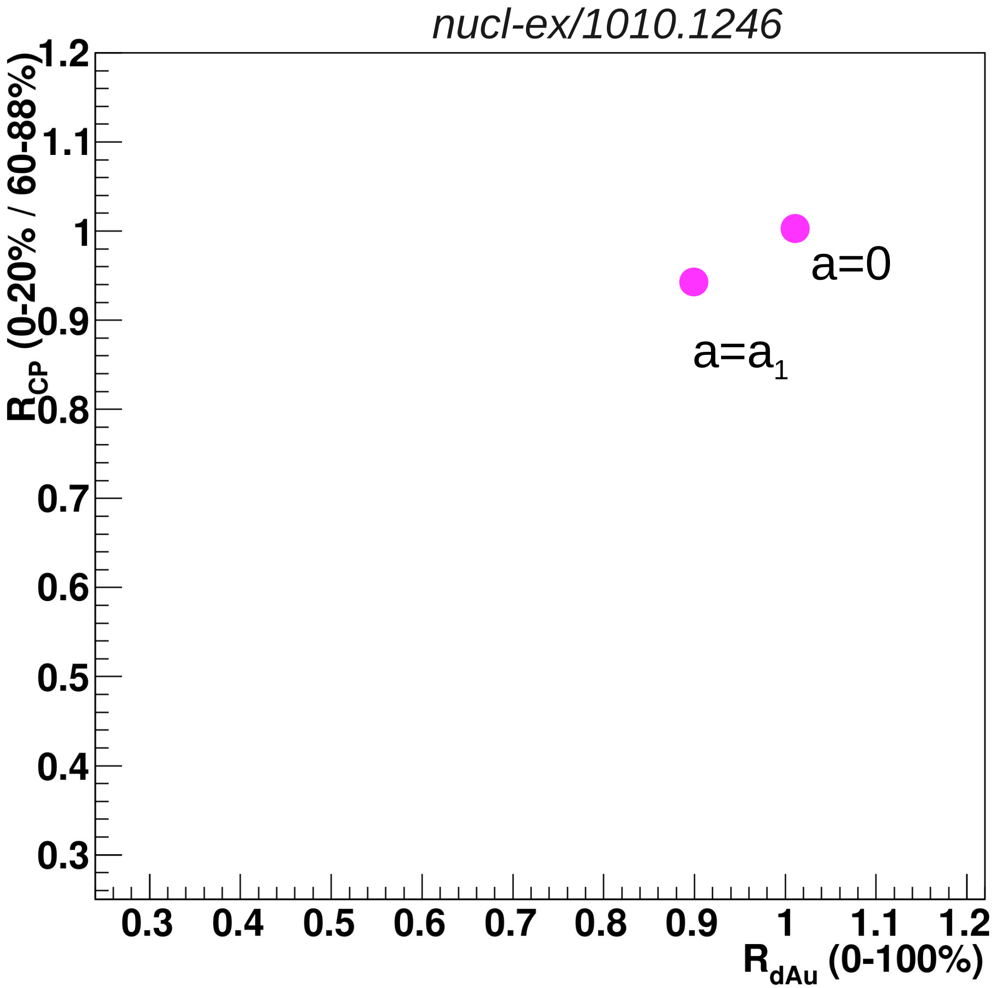

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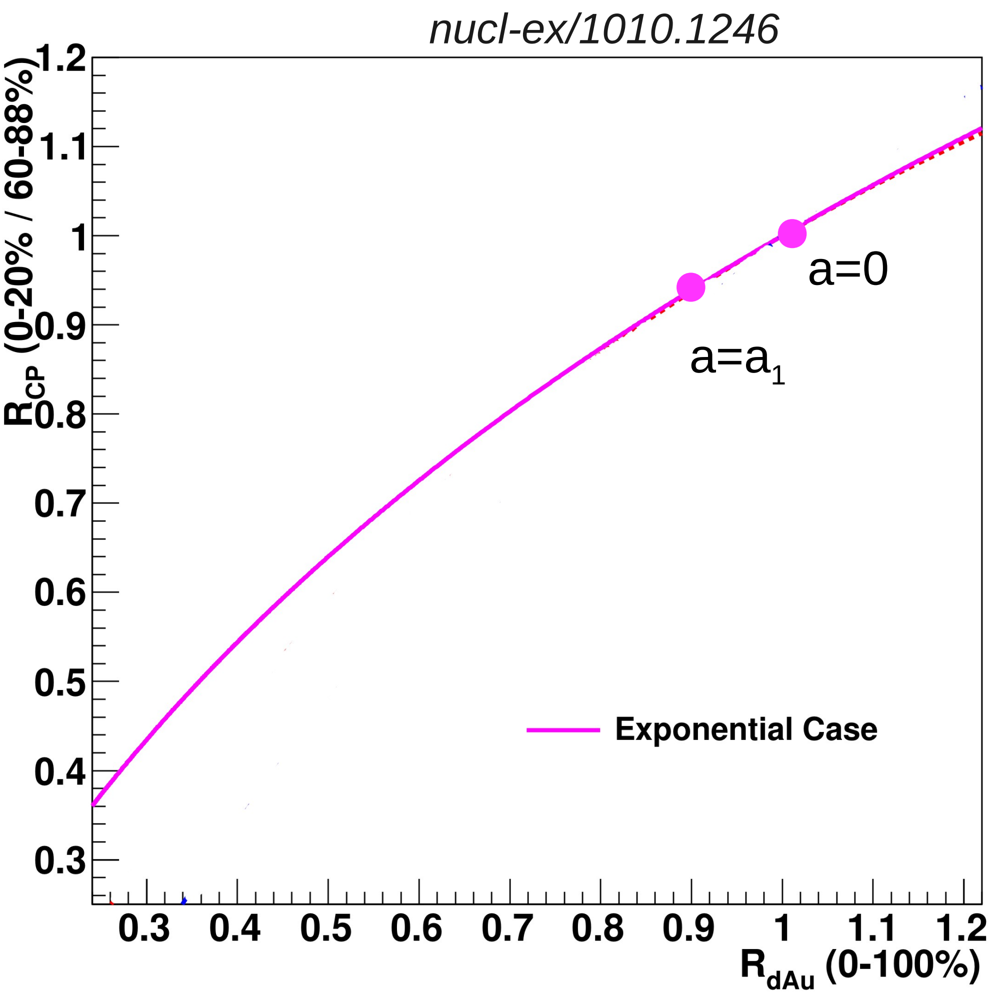
- As *a* is varied for a given modification function, it maps out a curve.
- Any model using a given functional form for $M(r_T)$ must fall on that curve.



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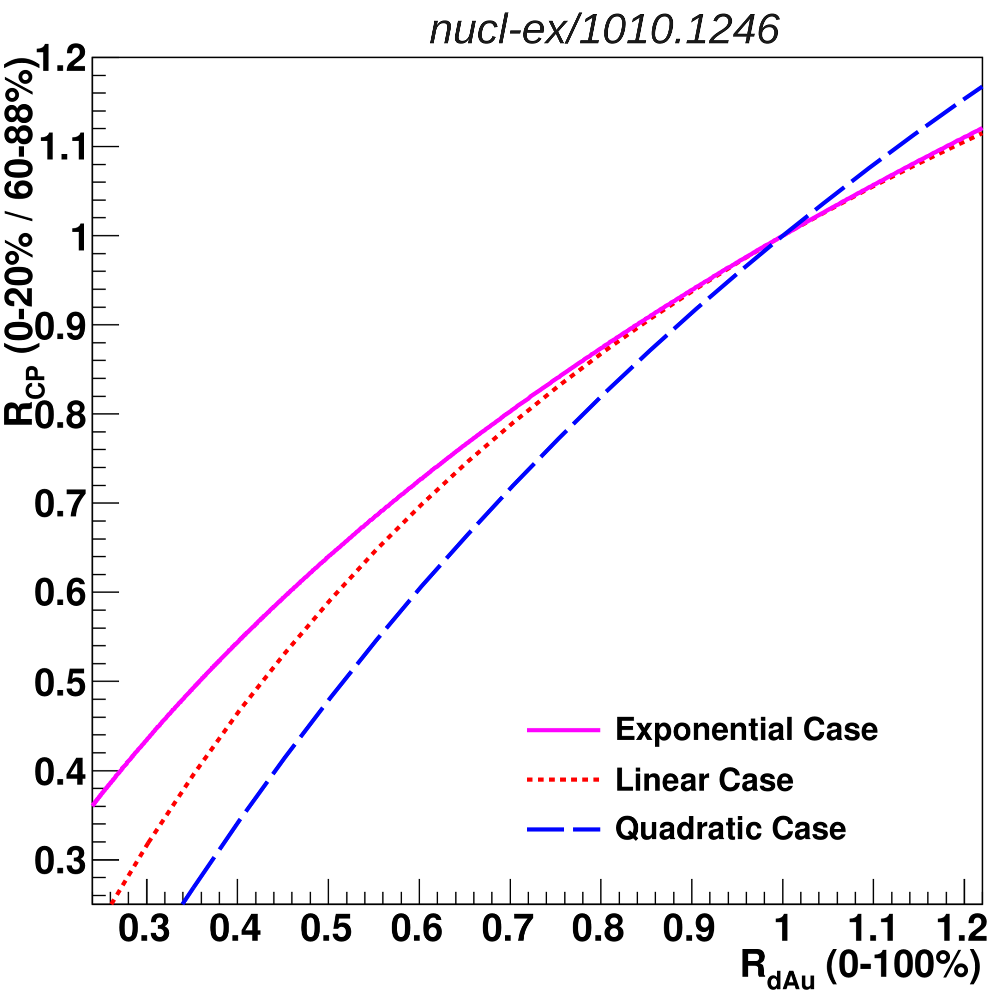

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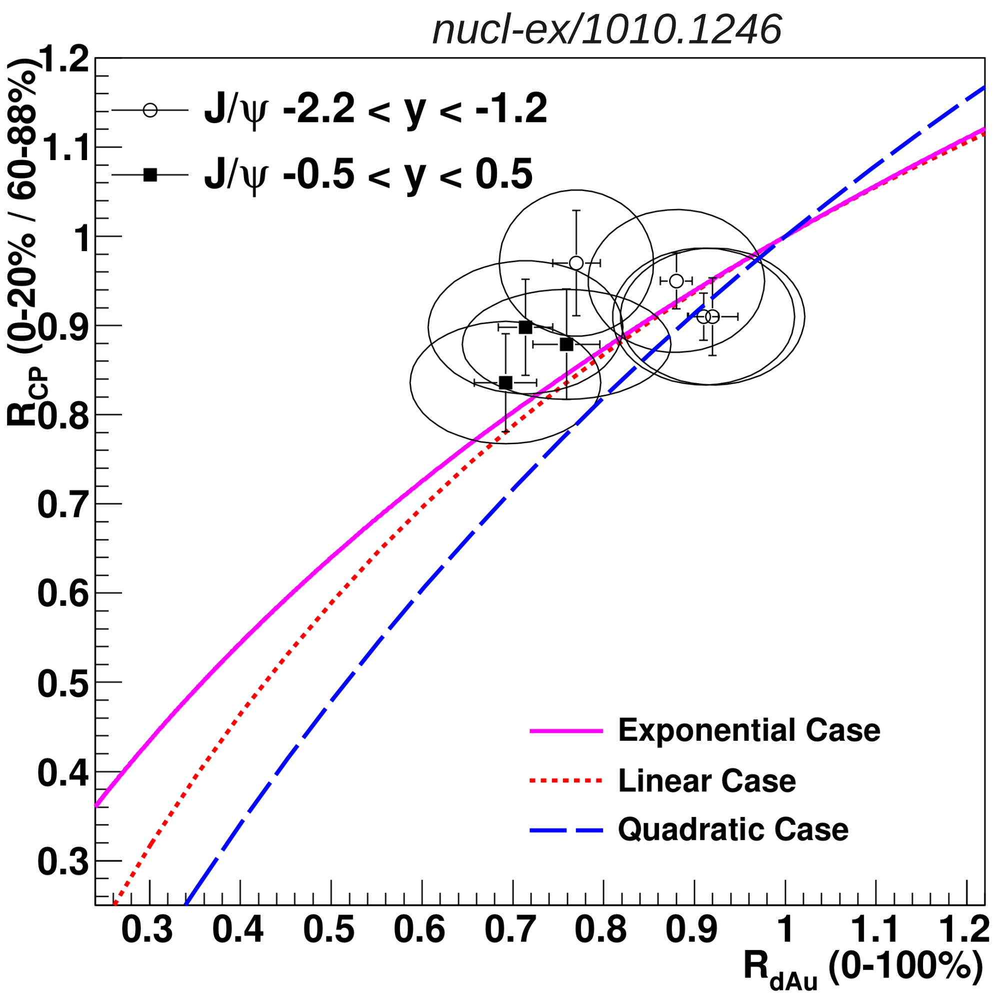
- Backward and mid rapidity data is unable to distinguish between the three cases shown here.




**Vertical(horizontal) bars** show point-to-point uncorrelated errors
**Ellipses** show point-to-point correlated systematic errors

# A Different Way to Look at the Centrality Dependence

- Backward and mid rapidity data is unable to distinguish between the three cases shown here.
- Forward rapidity data requires stronger than linear or exponential dependence on the thickness.
- Agreement with linear only gets worse if you add exponential.
- This is why the EPS09 (linear) + $\sigma_{br}$ (exponential) is unable to simultaneously reproduce $R_{cp}$ and $R_{dAu}$ data.

**Vertical(horizontal) bars** show point-to-point uncorrelated errors
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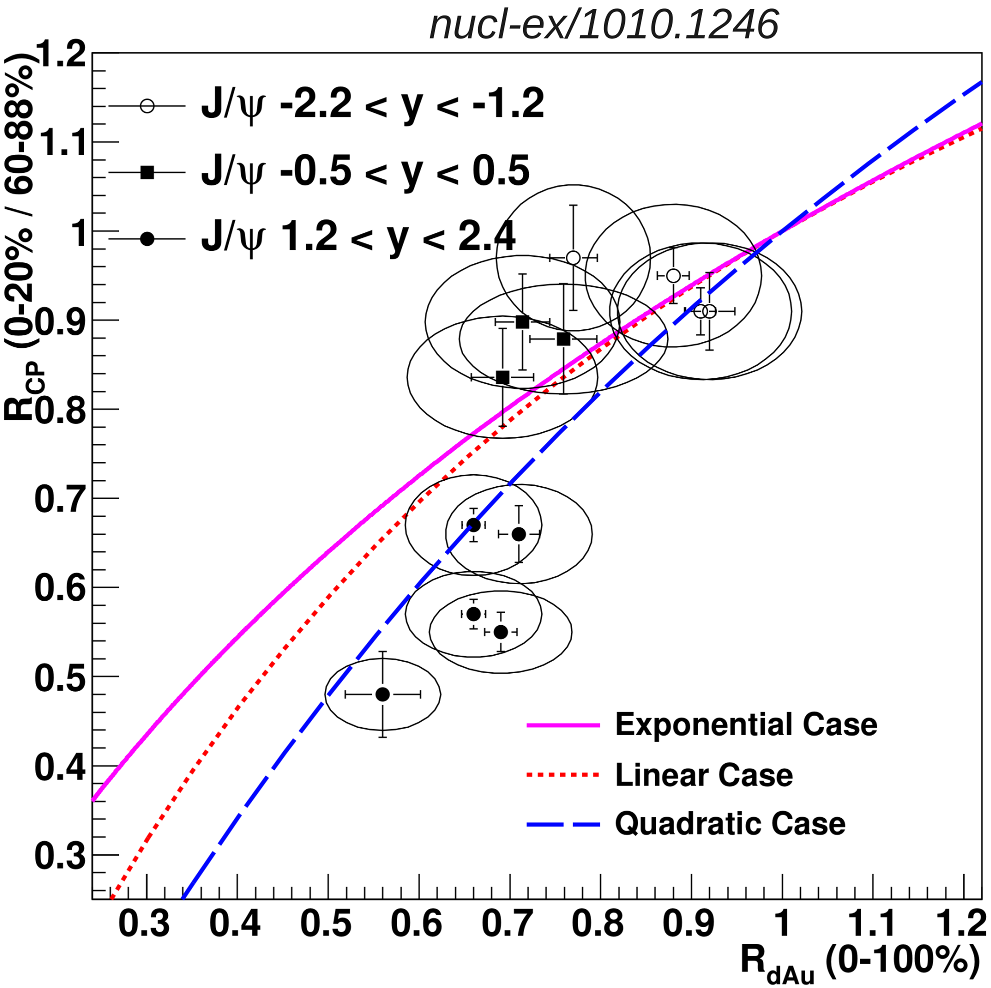
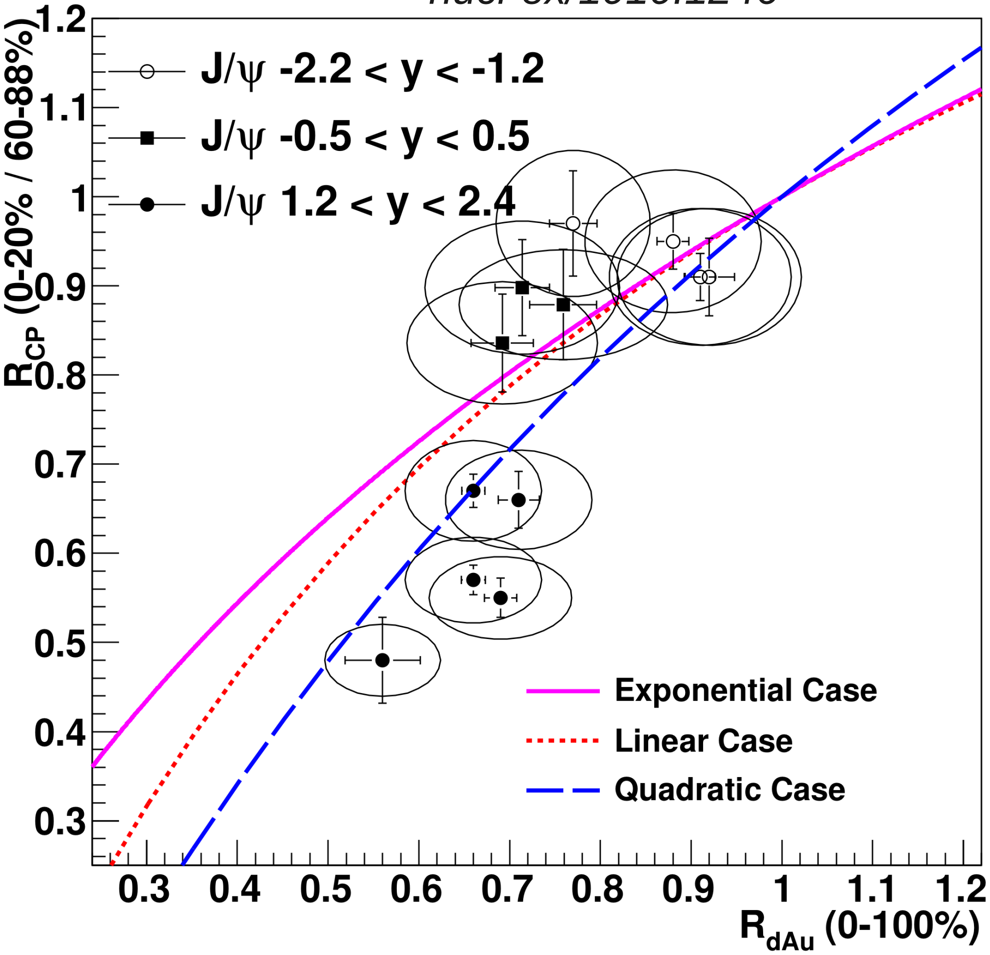


# A Different Way to Look at the Centrality Dependence

- EPS09 with **linear** thickness dependence **can not** describe the data at forward rapidity!
- Use the data to extract proper thickness dependence!

**Vertical(horizontal) bars** show point-to-point uncorrelated errors
**Ellipses** show point-to-point correlated systematic errors

*nucl-ex/1010.1246*



# What does this mean for Au+Au?

- Work is still ongoing to quantify CNM effects.
- We now have new high precision forward rapidity data from 2007.
- Can we learn anything about $R_{AA}$ in the meantime?

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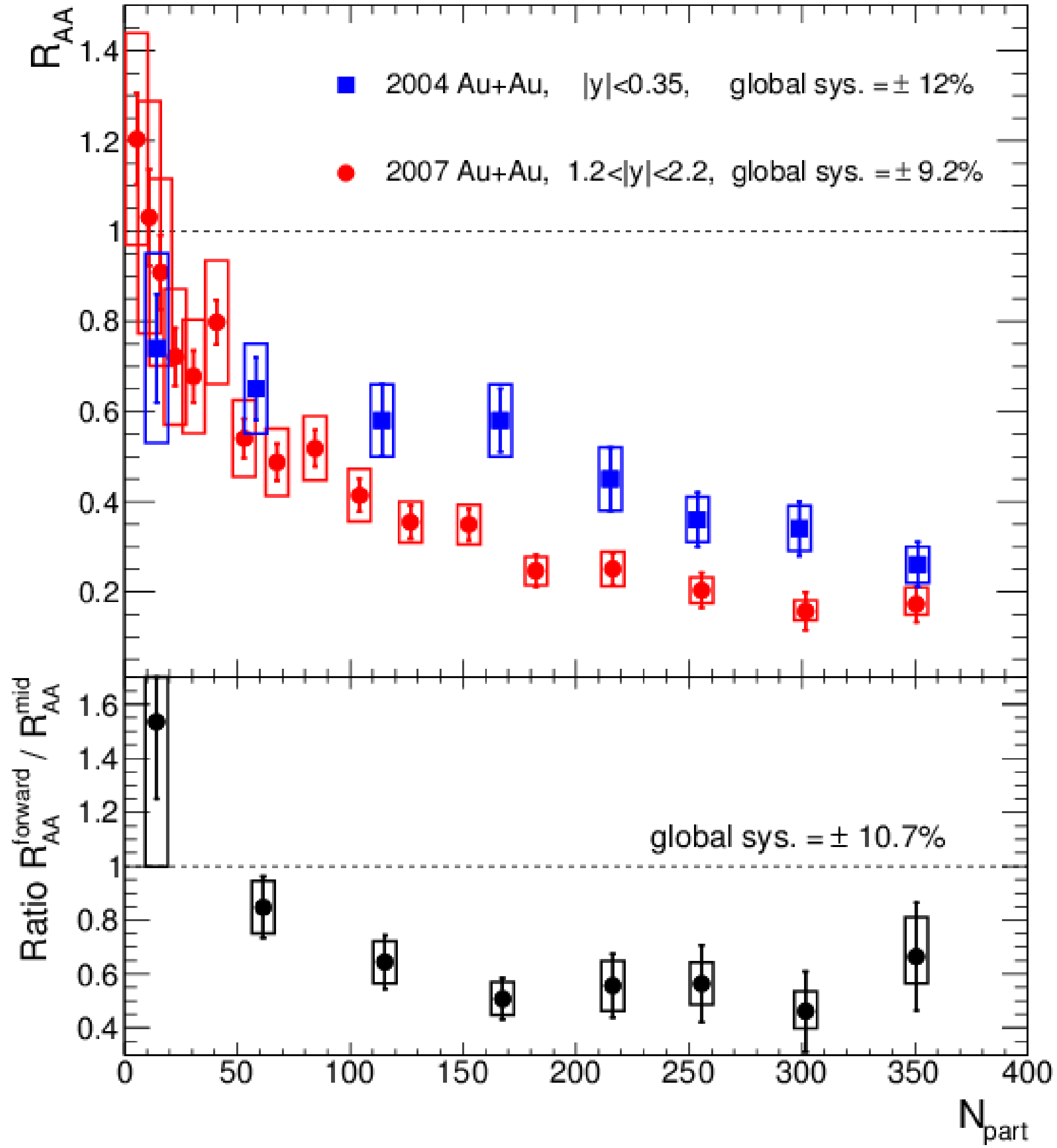
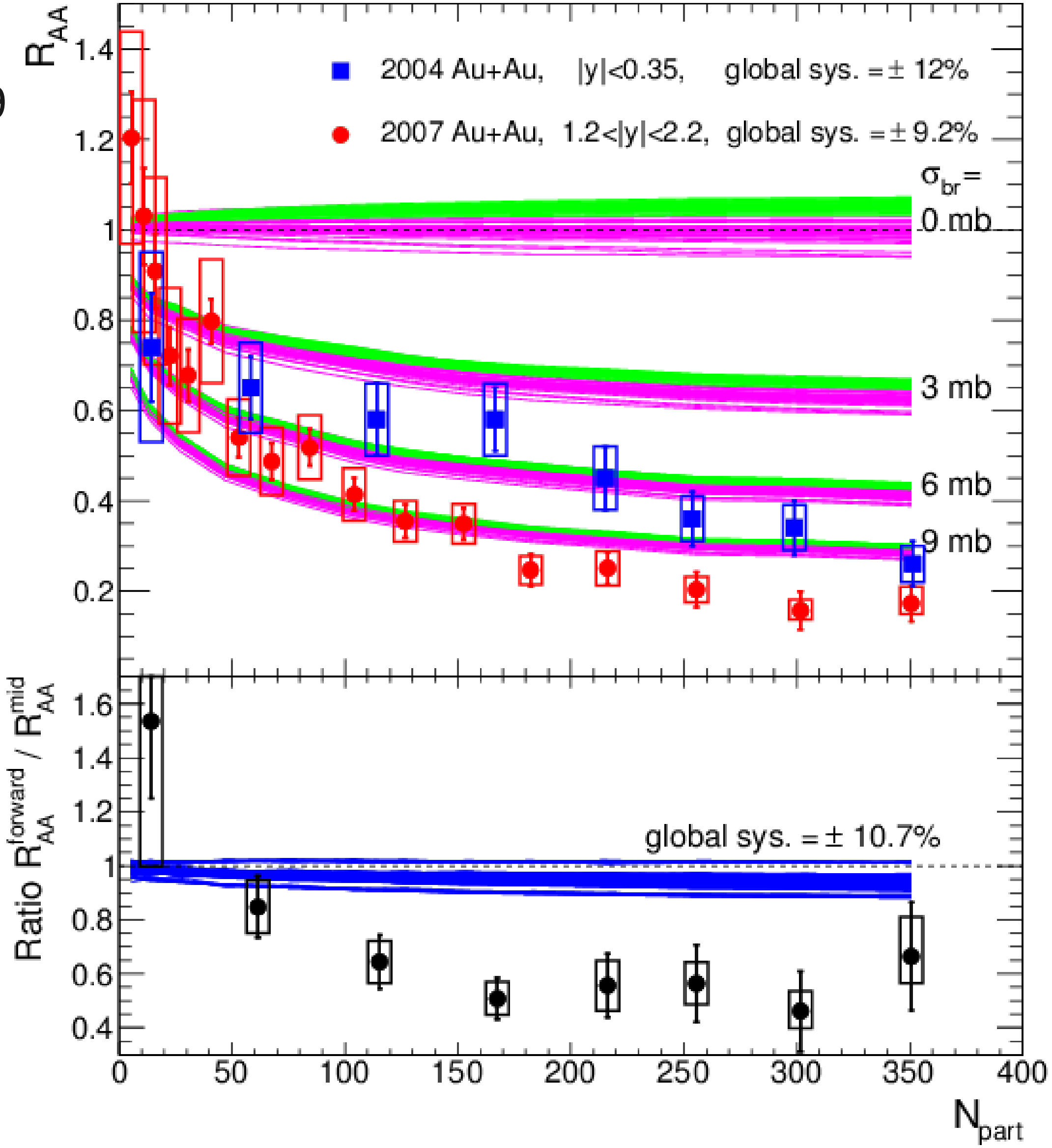


# What does this mean for Au+Au?

- Calculations show CNM effects extrapolated to Au+Au for (linear) EPS09 + (exponential) nuclear breakup.
- Green curves – predictions for |y|<0.35 for each of 31 EPS09 sets for 0, 3, 6, 9 mb breakup cross sections
- Magenta curves – same as green curves, but for 1.2<|y|<2.2
- Bottom panel shows the ratio of data & CNM predictions.

*nucl-ex/1103.6269*



# What does this mean for Au+Au?

- What do we learn from d+Au:
  - Linear EPS09 w/ a 4mb breakup cs adequately describes backward & midrapidity d+Au data, not sufficient at forward rapidity.
- What does this imply in Au+Au:
  - Suppression at **midrapidity** stronger than expected from d+Au alone.
  - Can not make a similar statement about the forward rapidity data until we understand d+Au at forward y.
  - Linear EPS09 does not explain difference of suppression with rapidity.
- Still, clear evidence of hot nuclear matter effects, although not yet quantifiable.

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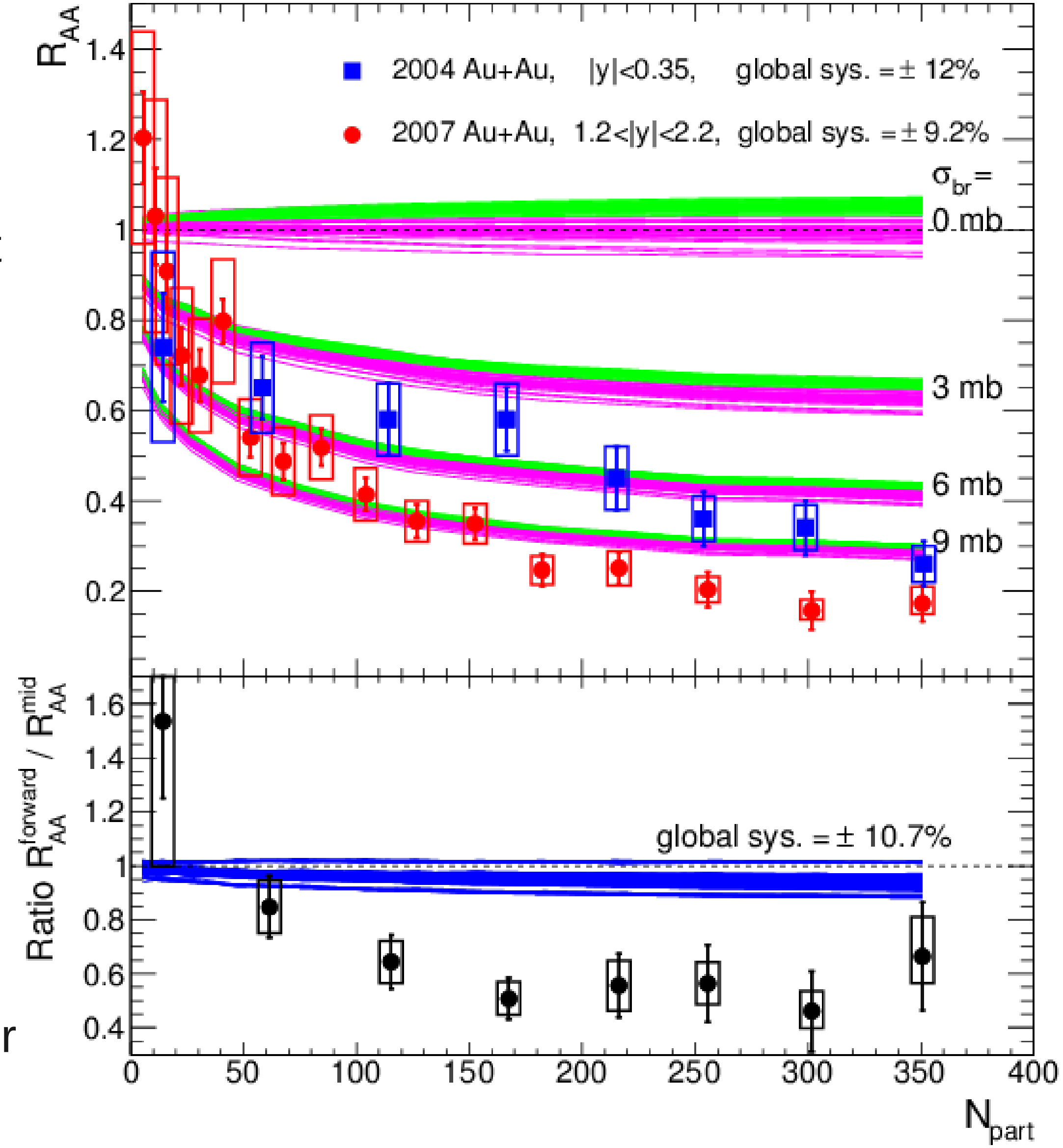

# Summary

- Understanding J/ψ CNM effects
  - New measurements of J/ψ in d+Au show that CNM effects are substantial, and must be taken into account.
  - New d+Au data requires suppression at forward rapidity which is stronger than linearly or exponentially dependent on nuclear thickness.
  - More detailed analysis of the d+Au data is ongoing to quantify aspects of the CNM effects.
- Understanding J/ψ suppression in Au+Au
  - New forward rapidity J/ψ data from 2007 increases precision.
  - Although CNM effects still not quantified at forward/backward rapidities, clear indication of hot nuclear matter effects present at midrapidity.
- Path Forward
  - Parametrize CNM effects at all y and predict effects in Au+Au.

# *Backup*

# What does this mean for Au+Au?

- CGC calculations for (blue) midrapidity and (red) forward rapidity J/ψ suppression.
- Overall normalization factor fixed to match the J/ψ suppression for central collisions at midrapidity.
- Good description of the forward rapidity data.
- Predicts enhancement for peripheral collisions at midrapidity, not seen in data.
- Predicts a similar enhancement at midrapidity in d+Au, also not seen in data.

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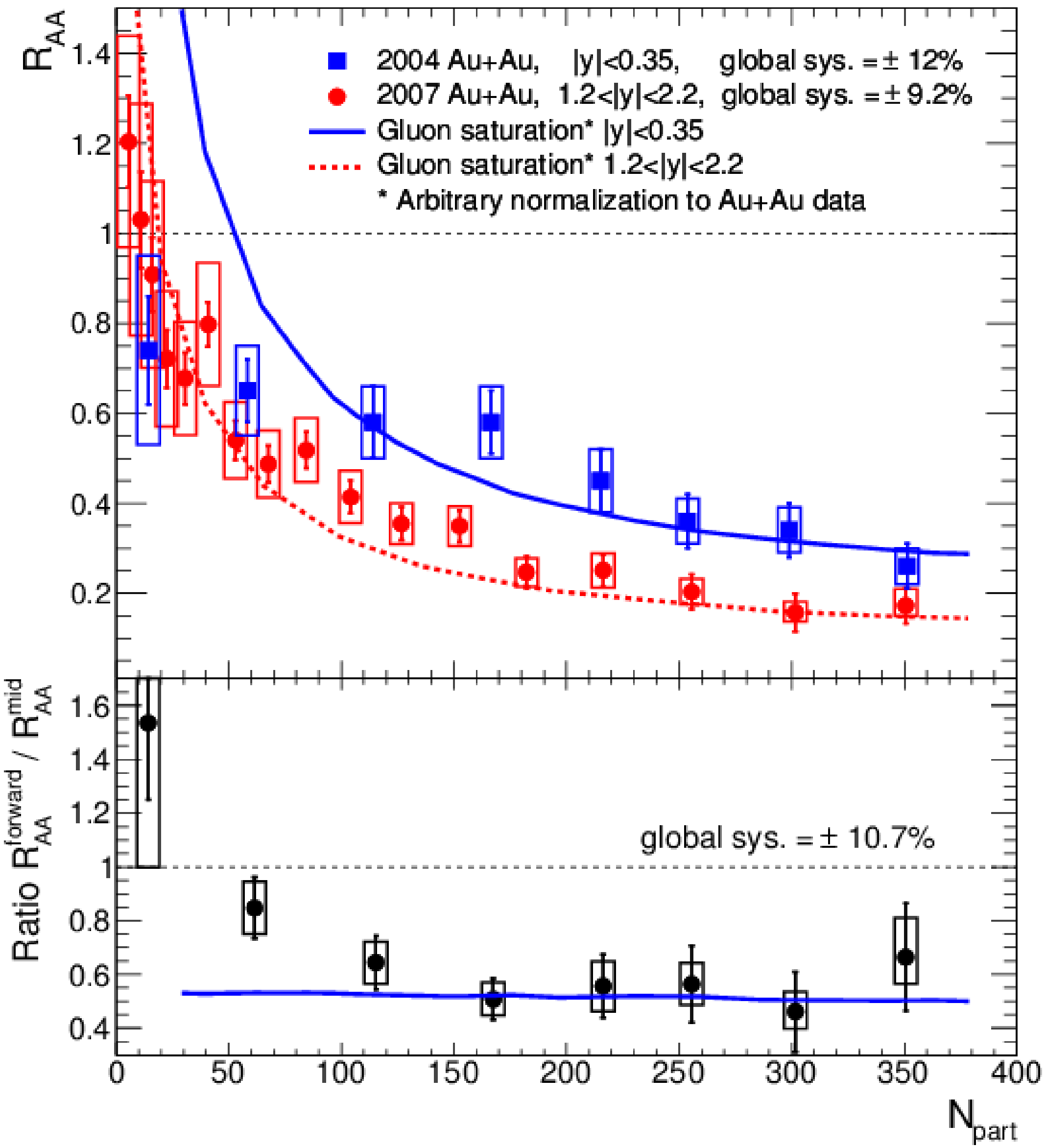
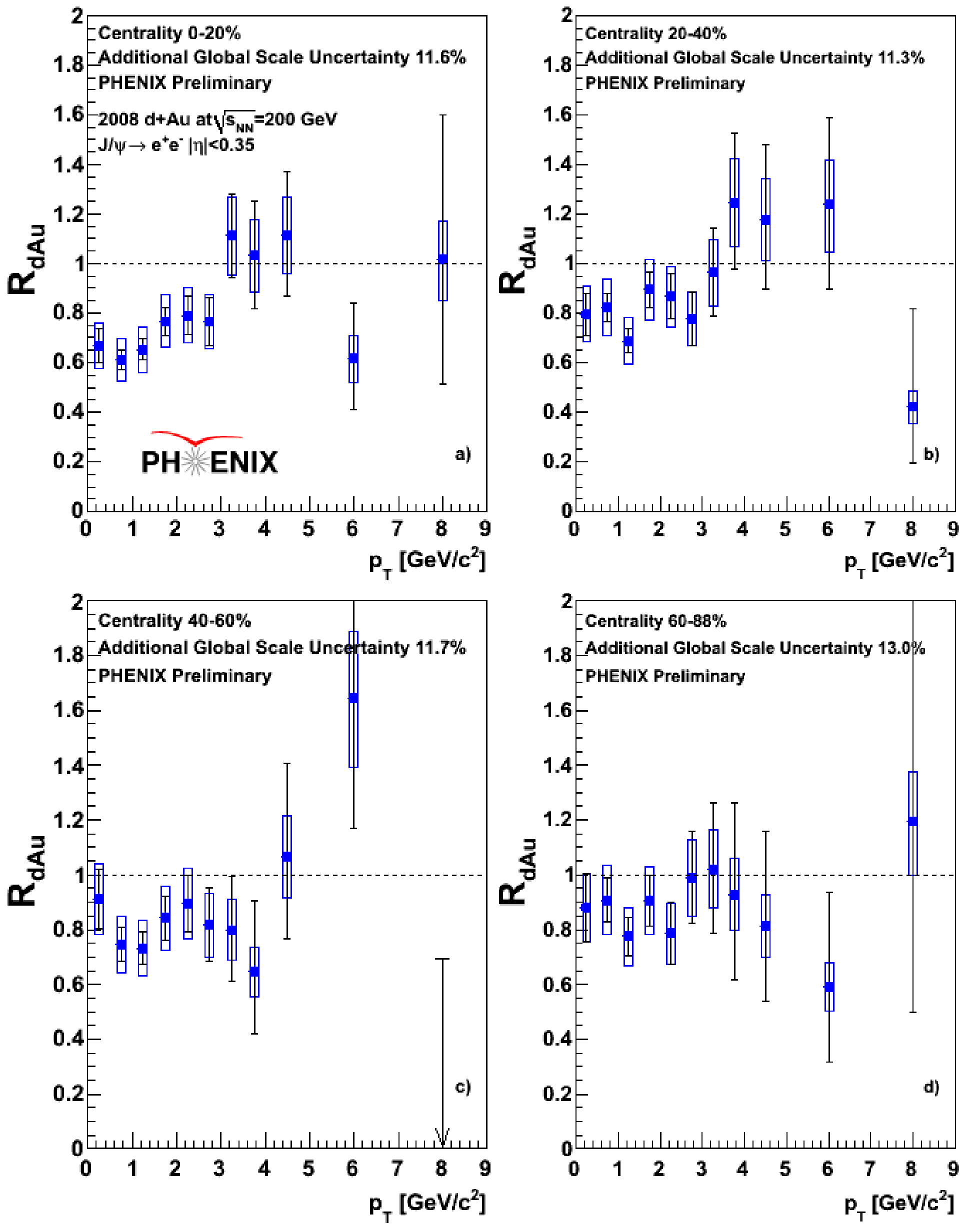


# $p_T$ Dependence of CNM Effects




- New preliminary results
- ~30-40% suppression at low $p_T$ for central d+Au collisions.
- This implies ~50% suppression for central Au+Au collisions
- Provides further constraints on CNM effects.

# Outline

1) ***The PHENIX detector.***

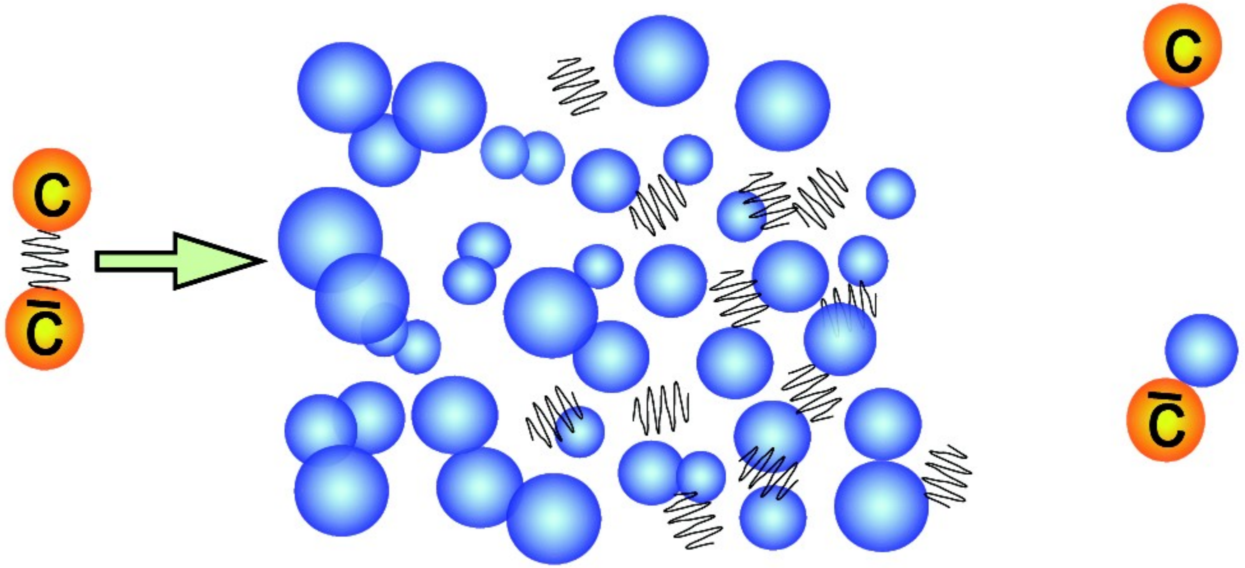
2) ***Open Heavy Flavor***

   a) Semileptonic decays of heavy quark mesons (D, B)

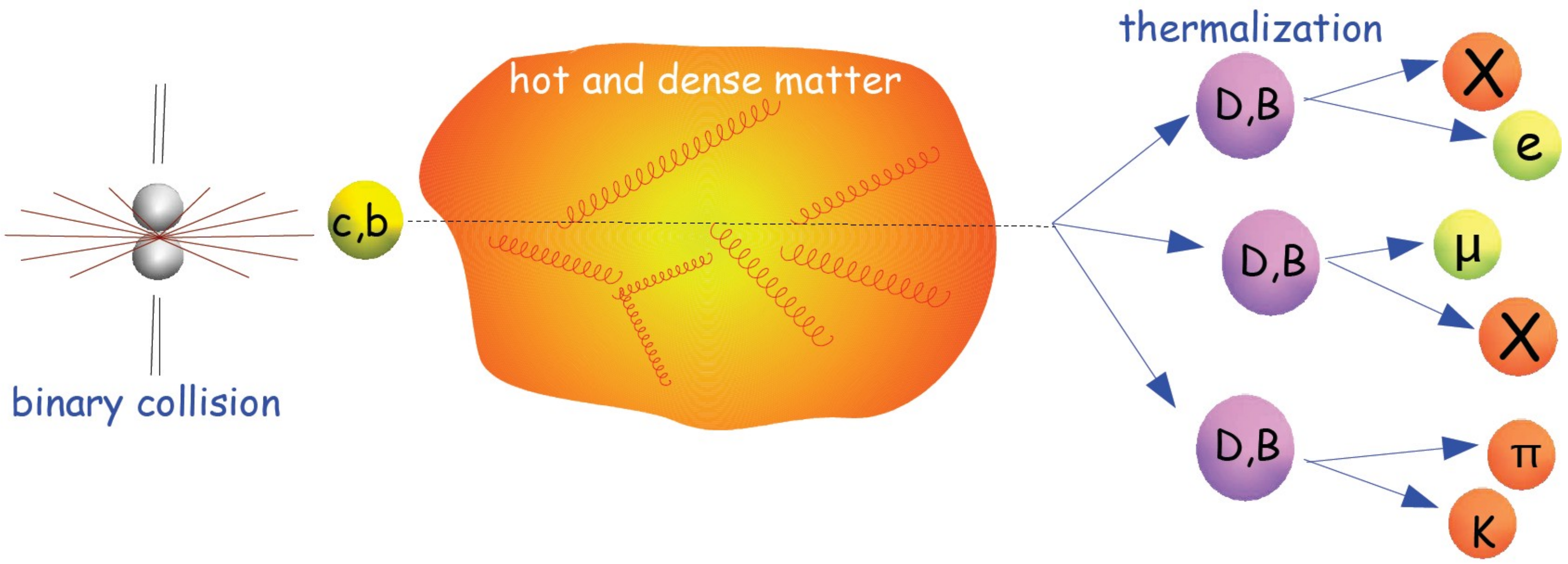
3) ***Closed Heavy Flavor – Quarkonia***

   a) J/ψ

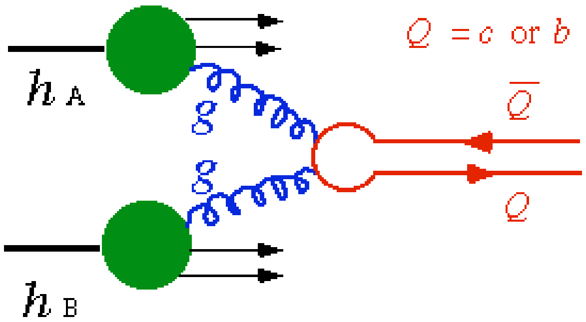
# *Closed Heavy Flavor – Quarkonia Production*



# *Open Heavy Flavor – Electrons from semileptonic decays*



# Heavy Quarks



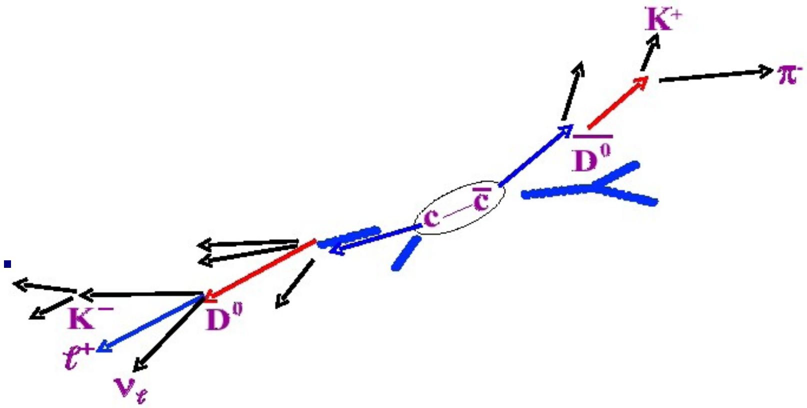

Charm & bottom quarks produced via gluon fusion during the initial collision.

They experience the full time-evolution of the medium.

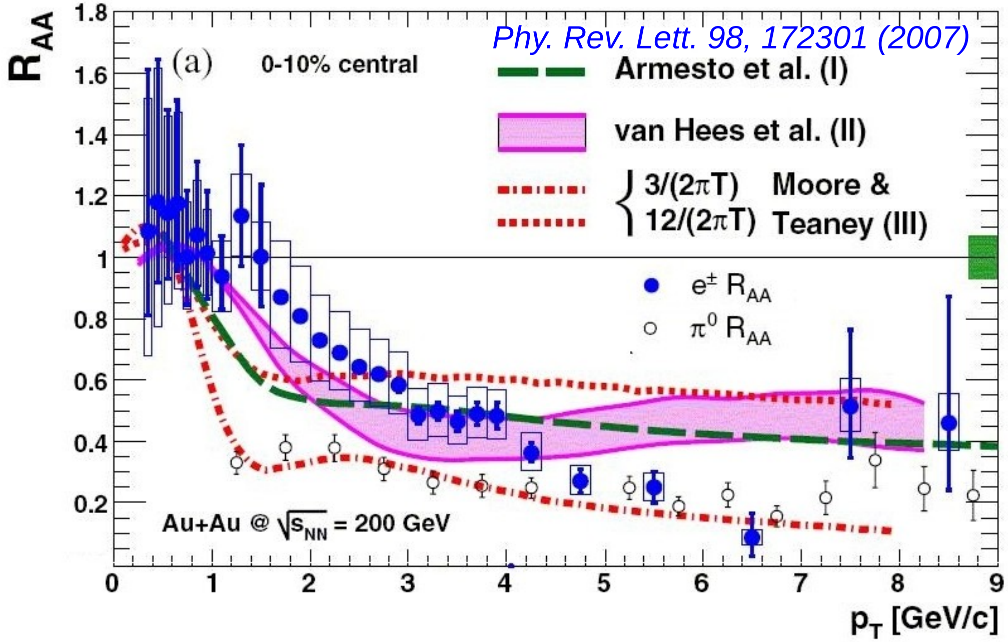
$$R_{AA}^{bottom} > R_{AA}^{charm} > R_{AA}^{u,d}$$

Heavier quarks are expected to lose less energy in the medium.

At PHENIX, measured through their semileptonic decays of D, B mesons.



# Heavy Flavor in Au+Au




- Measured $R_{AA}$ of electrons from D, B mesons (mixture of c/b quarks).
- Roughly 50% c/b at ~4 GeV/c.
- Heavy quarks show large suppression in Au+Au.
- What about effects from a nuclear target, termed Cold Nuclear Matter (CNM) effects?

$$R_{AA} = \frac{dN^{AA}/dy}{dN^{pp}/dy\, N_{Coll}}$$

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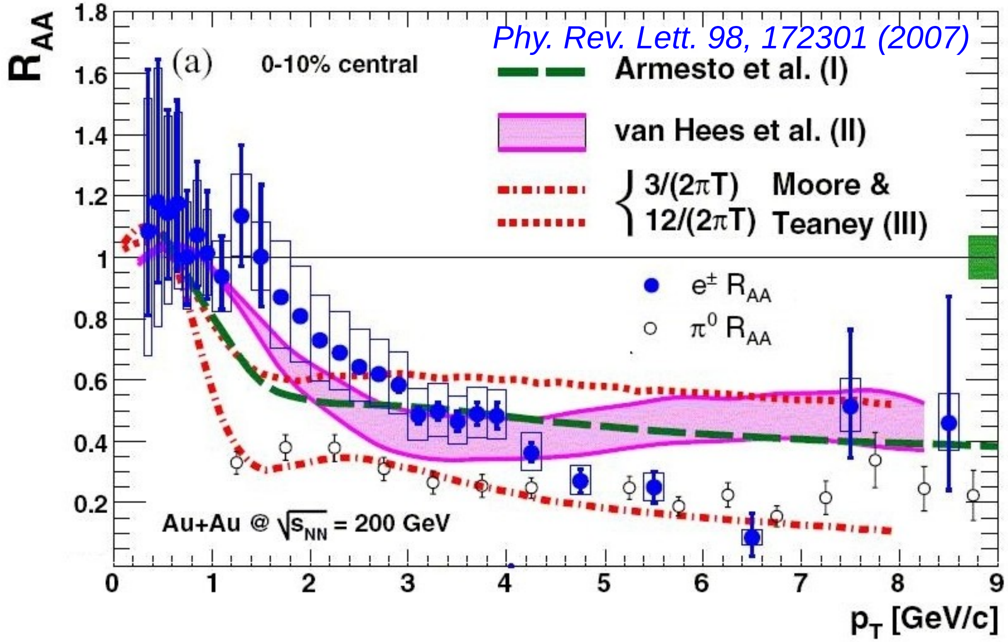
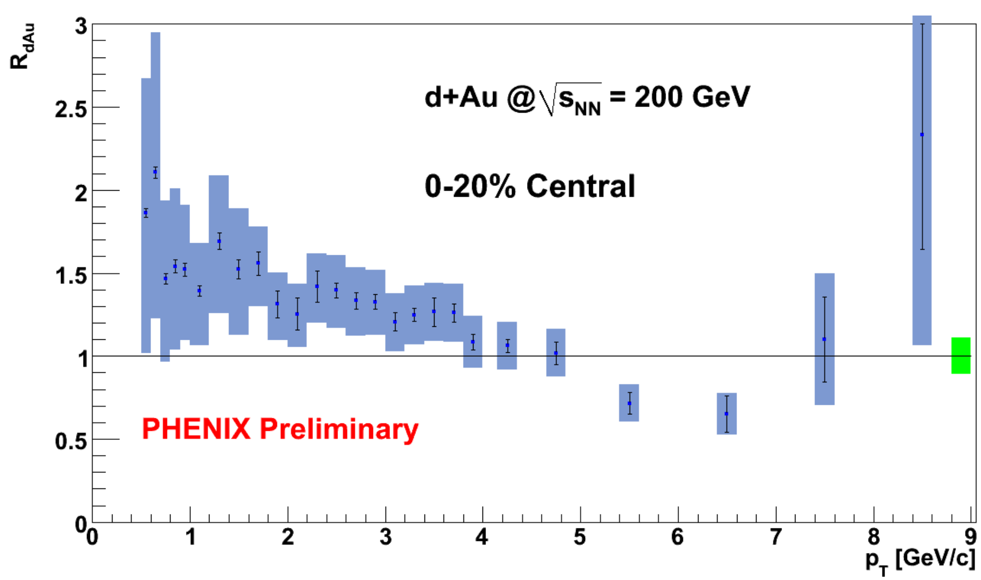
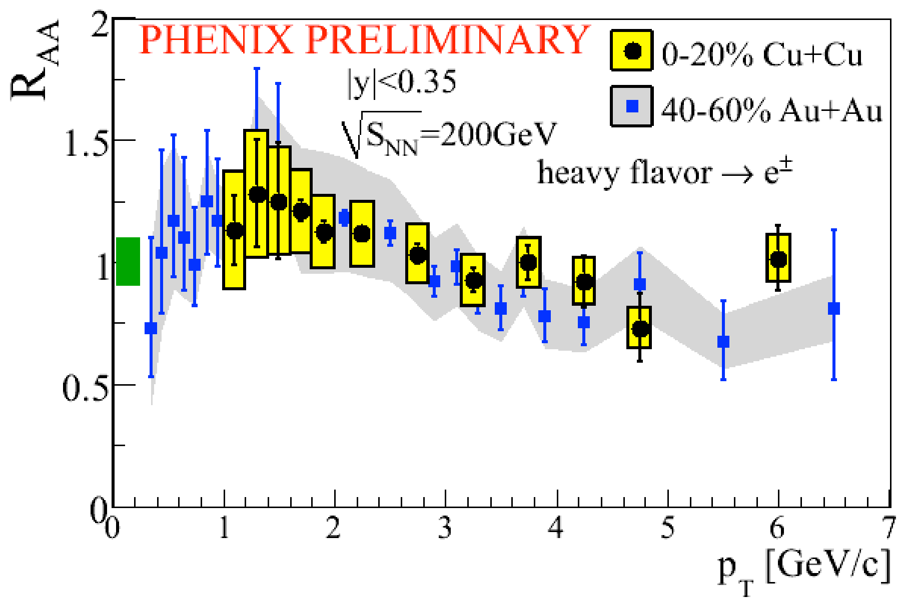
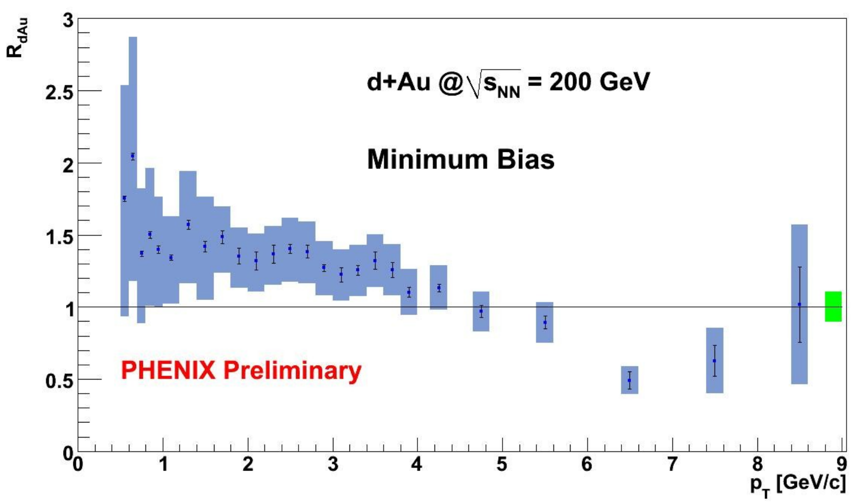



- Measured $R_{AA}$ of electrons from D, B mesons (mixture of c/b quarks).
- Roughly 50% c/b at ~4 GeV/c.
- Heavy quarks show large suppression in Au+Au.
- What about effects from a nuclear target, termed Cold Nuclear Matter (CNM) effects?
- New preliminary results from the 2008 d+Au run allow us to quantify these effects.
- CNM effects seem to explain only a small fraction of the suppression seen in Au+Au.

# Heavy Flavor in Au+Au

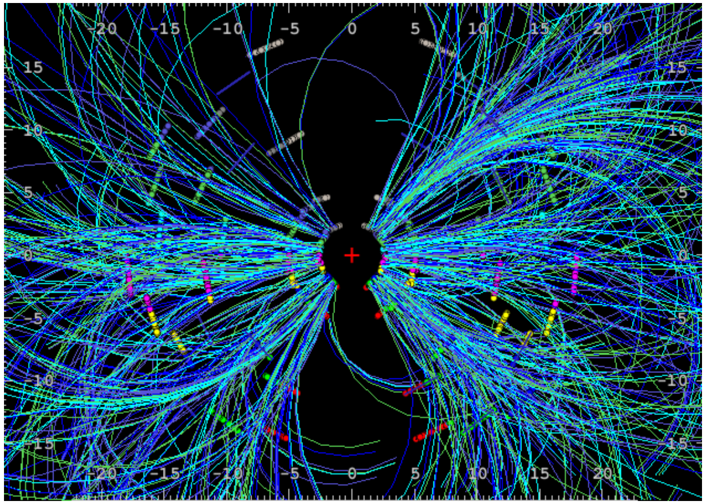



- Also measure HF by varying centrality and ion species.
- New preliminary results from Cu+Cu.
- Central Cu+Cu and semi-peripheral Au+Au show similar levels of suppression.
- d+Au results suggest CNM effects may dominate here.

# Future Measurements

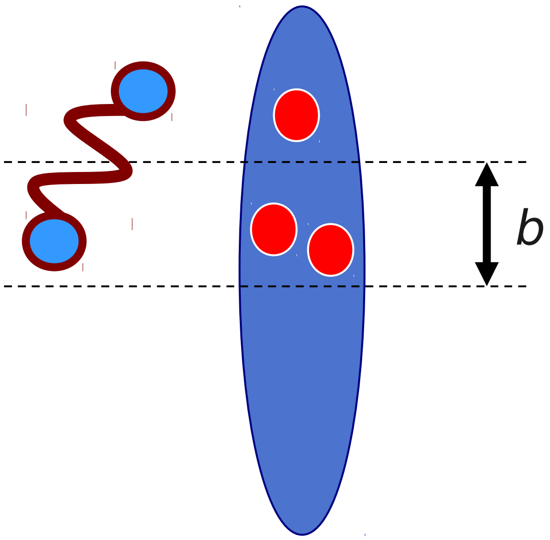
- PHENIX near-term upgrades include the Installation of two vertex detectors.
- They will provide a large reduction of backgrounds.
- Allow measurements of c/b separation through displaced vertex measurements.



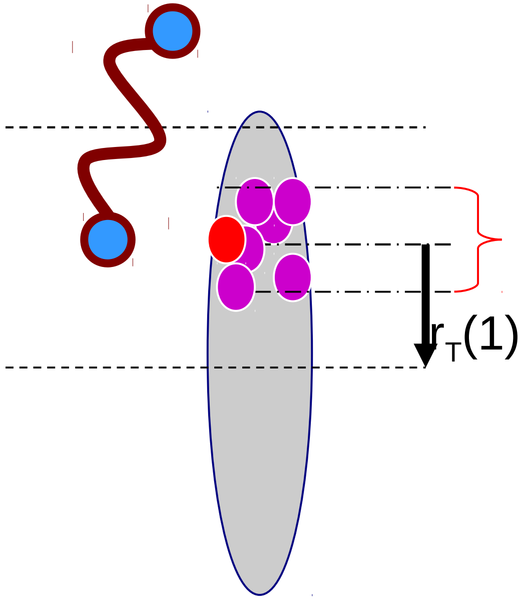

- VTX (|y|<1)
  - Installed successfully in 2011
- FVTX (1.2<|y|<2.4)
  - To be installed in 2012
  - Will also improve mass resolution – ψ' measurement in muon arms

# More on Centrality

- Divide BBC(S) charge into percentile bins
- Use Glauber MC and simulation of BBC response to link charge with $\langle N_{coll} \rangle$ or impact parameter (*b*)
- Currently use 4 centrality bins (0-20%, 20-40%, 40-60%, 60-88%)



# Density Fluctuations

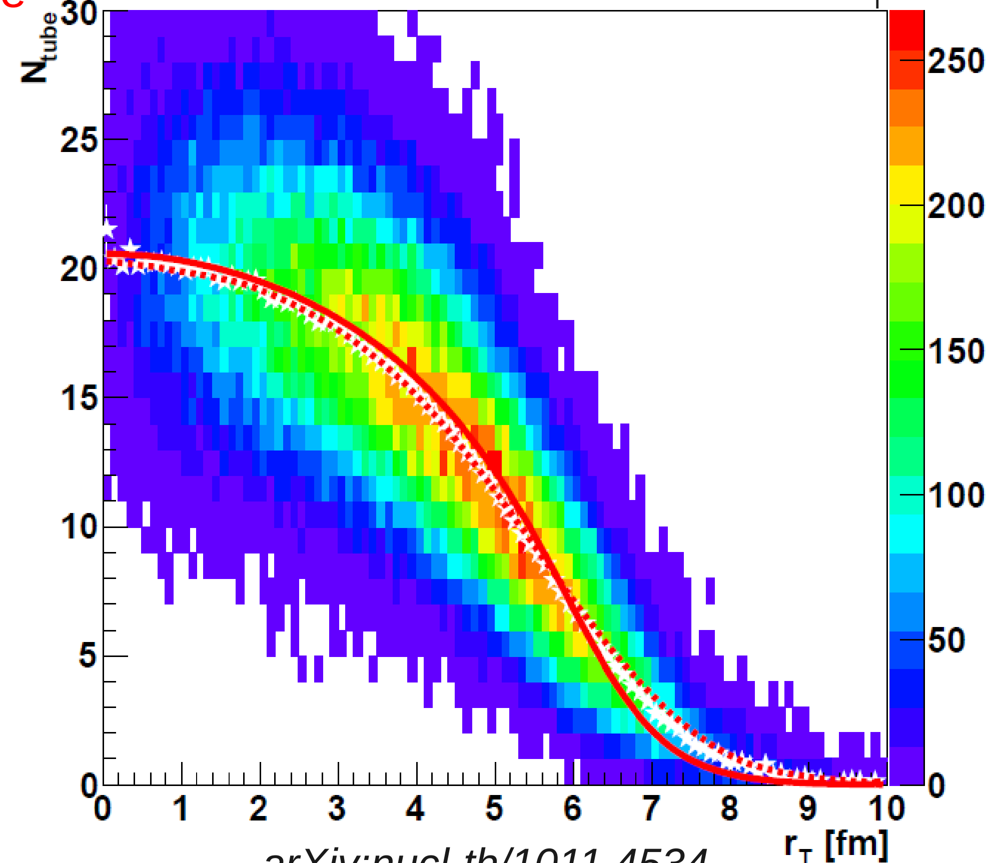



For each binary collision at $r_T$, count the number of other nucleons in the nucleus inside the tube defined by
$r_T \pm 2 \times 0.877$ fm

In this example, the $\mathbf{N_{tube}} = 6$.

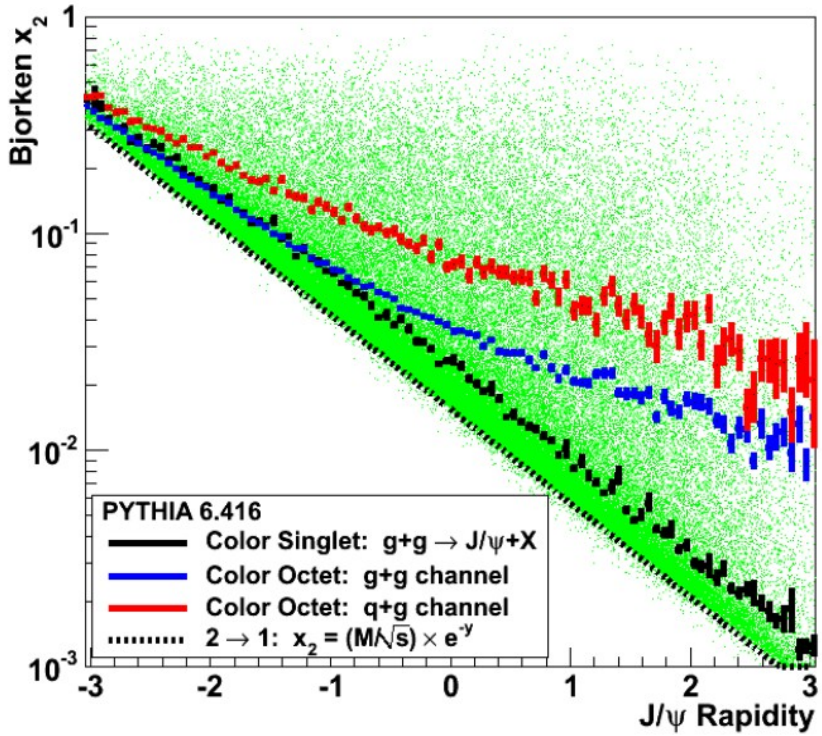
Maybe the nuclear modification is related to the fluctuating quantity relating to $N_{tube}$, rather than the average thickness $\Lambda(r_T)$

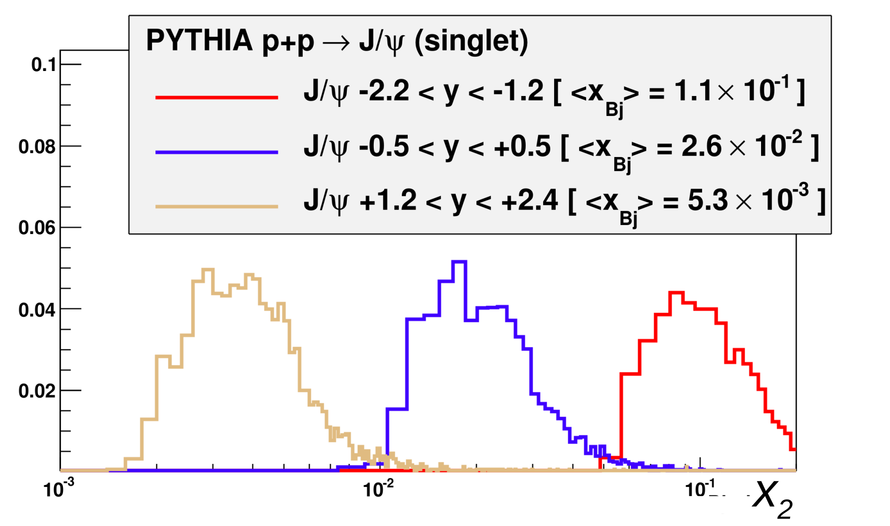
**White Points:** Mean $N_{tube}$
**Solid Red Curve:** $\Lambda(r_T)$
**Dashed Red Curve:** smeared $\Lambda(r_T)$ by $R_{tube}$




*arXiv:nucl-th/1011.4534*

# Bjorken x Probed by PHENIX




PHENIX probes three ranges of *x* in the gold nucleus.

- forward *y*, *x*~0.005
- mid *y*, *x*~0.03
- backward *y*, *x*~0.1